

Quasi-static and dynamic order-disorder transition in presence of strong pinning

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(Dated: March 7, 2008)

We present the results of an experimental study of vortex dynamics in non-twinned $YBa_2Cu_3O_{6.87}$ crystal. It is found that critical currents J_c and $J_{c,dyn}$, which correspond to the pinning force in the thermal creep and flux flow mode, respectively, non-monotonically vary with the magnetic field. However, the minimum in the $J_{c,dyn}(H)$ dependence is observed in higher fields, compared with the minimum position H_{OD} in the $J_c(H)$ dependence. Considering that the field H_{OD} corresponds to the static order-disorder transition, this difference is explained by partial dynamic ordering of the vortex solid. It is concluded that finite transverse barriers guarantee finite density of transverse displacements of vortex lines $u_t \simeq c_L a_0$ suitable for preservation of the disordered state of the moving vortex solid.

PACS numbers: 74.25.Qt, 74.25.Sv, 74.72.Bk

The interaction of static and dynamic elastic media with chaotic pinning potential is one of the chapters of solid state physics, which includes dislocations in solids, charge density waves, Vigner crystals, and vortex lattices (VL's) in Type-II superconductors. The VL's are the most appropriate objects for the experimental study of elastic media, because it is easy to change the strength of pinning potential in superconductors, as well as the elasticity and motion velocity of VL's. An important feature of the VL's is the non-monotonous field variation of the pinning force F_p , which is observed in low- T_c (NbSe₂ [1, 2], V₃Si [3]) middle- T_c (MgB₂ [4, 5]), and high- T_c (BiSrCaCuO [6], YBaCuO [7, 8]) superconductors. The increase of the pinning force can be explained by softening of the elastic moduli of VL's in vicinity of the upper critical field $H_{c2}(T)$ [2] or the melting line $H_m(T)$ [9] that causes better adaptation of the vortex lines to the pinning landscape. Some alternative models [10, 11] suggest formation of an ordered vortex solid (VS) in low fields, which transforms into a disordered one in some magnetic field H_{OD} , though the nature of the order-disorder (OD) transition and the mechanism of increasing the force F_p may be different. These models are supported by correlation between the field H_{OD} corresponded to the structural OD transition [12] and the onset of the F_p increase [6] in BiCaSrCuO crystals. An actual problem of the VS phase is the nature of its ordering under an increased vortex velocity v . The "shaking temperature" model [13] suggests that transverse vortex displacements u_t induced by the disorder reduce with increased velocity, $u_t \propto 1/v$; and the increase of the velocity above some critical value v_c results in a dynamic transition from the disordered to ordered state. It was later justified [14] that the increase in

v leads to a suppression of the pinning in the longitudinal (with respect to \mathbf{v}) direction only, while pinning barriers remain finite in the transverse direction. The effect of motion on the transverse barriers, phase state and pinning force of vortex solid is still controversial issue, and this subject first of all requires additional reliable experimental studies. The goal of this work is experimental study of vortex dynamics in the presence of strong pinning.

The measurements were performed on detwinned $YBa_2Cu_3O_{7-\delta}$ crystal, annealed in an oxygen atmosphere at 500°C for one week. Such anneal corresponded to an oxygen deficiency $\delta \simeq 0.13$ [15] and $T_c \simeq 91.8$ K. The crystal then was held at room temperature for 7 days to form clusters of oxygen vacancies, which reduced the tension of the field H_{OD} [16]. The field variation of the pinning force was studied through measurement of the current-voltage characteristics, $E(J)$, using the standard four-probe method with dc current. The investigated sample had rectangular shape with smooth surfaces; its dimensions were $3.5 \times 0.4 \times 0.02$ mm with the smallest dimension along the c axis; the current was applied along the largest dimension; and the distance between the current and potential contacts, and between the potential contacts was about 0.5 mm. The measurements were performed at a temperature of 86.7 K in the field $\mathbf{H} \parallel \mathbf{c}$. Fig. 1 shows the $v(J) = cE(J)/B$ dependencies and current variation of the normalized dynamic resistance $\rho_d(J) \equiv [dE(j)/dJ]/\rho_{BS}$, where $\rho_{BS} = \rho_N B/B_{c2}$ [7]. At low currents, the electric field increases exponentially with an increase in current and the resistance ρ_d is much lower than one. This increase in v and low dynamic resistance indicate the presence of thermally activated vortex creep. At high currents, the $v(J)$ dependence is linear and the value of ρ_d is close to 1, indicating the presence of the flux flow mode. The critical current in the thermal creep mode J_E can be characterized by the voltage

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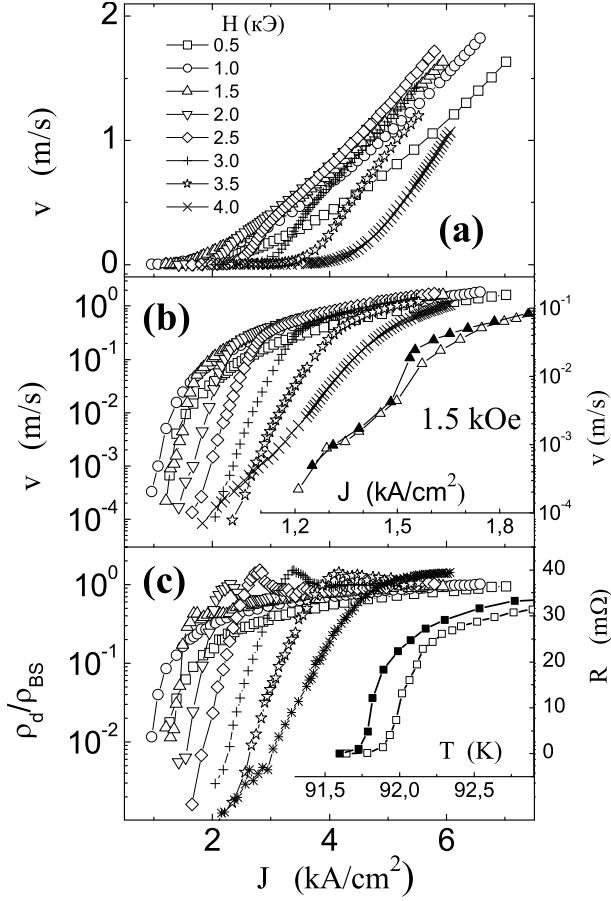


FIG. 1: $E(J)$ curves presented in the linear (a) and semi-logarithmical scale (b), and $\rho_d(J)$ curves presented in the semi-logarithmical scale (c). The inset in panel (b) shows the $E(J)$ dependencies measured upon increase (light symbols) and decrease (dark symbols) of the current.

criteria of $E = 1 \mu\text{V}/\text{cm}$ and $E = 100 \mu\text{V}/\text{cm}$, and the dynamic critical current $J_{c,dyn}$ can be determined by extrapolating the linear parts of the $v(J)$ dependence, corresponded to the flux flow mode, to zero voltage [17]. Field variation of the currents J_E and $J_{c,dyn}$ normalized by their values in a field of 0.5 kOe are shown in Fig. 2a. It is seen that the currents J_c and $J_{c,dyn}$ start to increase in the fields above 1.25 kOe and 2.5 kOe, respectively, which are substantially smaller in comparison with the fields H_{c2} and H_m . Therefore this increase can not be caused by better adaptation of the vortices to the pinning landscape induced by softening of the elastic moduli. Obtained field variation of the currents J_E and $J_{c,dyn}$, and the peculiarities of vortex dynamics can be explained in frames of the model proposed by Ertas and Nelson [10]. It is assumed that the OD transition occurs when transverse displacements of vortex lines exceed the value of $c_L a_0$, where $a_0 \simeq \sqrt{\Phi_0/B}$ is inter-vortex distance, Φ_0 is the flux quantum, and c_L is the Lindemann number. The field is defined by equality of energies $E_{el}(H_{OD}) = E_p(H_{OD})$, where E_p is the pinning

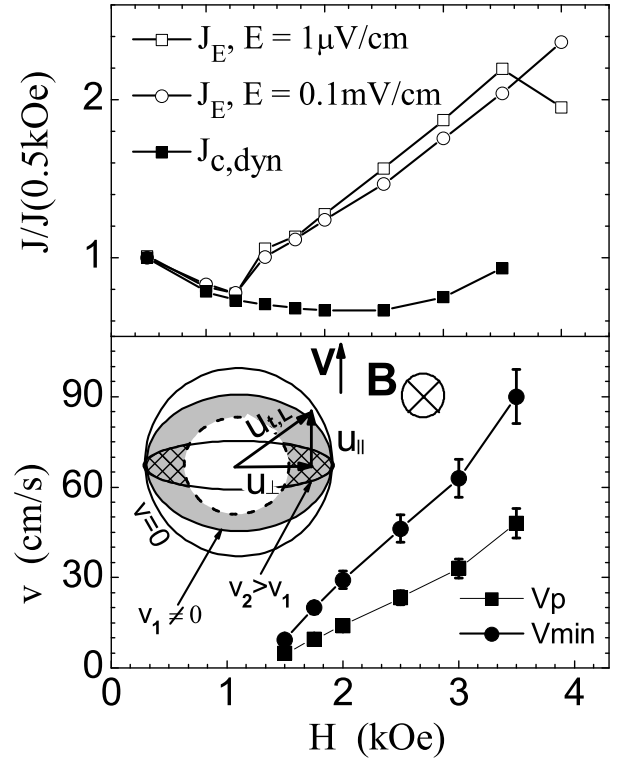


FIG. 2: (a) Field variation of the current $J_{c,dyn}$ and J_E normalized by their values in a field of 0.5 kOe. (b) Field variation of the velocities v_p and v_{min} correspondent to the peak and minimum position in the $\rho_d(J)$ dependencies, respectively. The inset in panel (b) shows sketch of the transverse vortex displacement $u_{t,L}$ correspondent to the Lindemann criteria. Dash and solid circles correspond to the lower and upper boundaries of the displacements $u_{t,L}$ (see the text), respectively, in the static VS in magnetic field $H > H_{OD}$. Dot ellipses show evolution of the maximal displacements $u_{t,L}$ upon increase of the velocity v . Dashed region corresponds to the displacements $u_{t,L}$ in the dynamic VS.

energy, $E_{el} \simeq c_L^2 \varepsilon \varepsilon_0 a_0$ is increase of the elastic energy caused by displacements $u_t = c_L a_0$, ε is the anisotropy parameter, $\varepsilon_0 = (\Phi_0/4\pi\lambda)^2$ is the line tension of vortex line and λ is the penetration depth. As evident from Fig. 2a, the minimum position does not depend on the driving force within the creep regime in agreement with magnetization measurements [7, 8]. This means that the value of ratio E_{el}/E_p , and, therefore the energy E_p , is not changed, indicating that minimum in the $J_E(H)$ curve corresponds to static OD transition, $H_{OD} \simeq 1.25$ kOe. Estimations presented below show that static OD transition in our sample is caused by vortex interaction with the clusters of oxygen vacancies rather than with the isolated oxygen vacancies. Indeed, for the point disorder the pinning energy is [10, 18] $E_p \simeq (\gamma \varepsilon^2 \varepsilon_0 \xi^4)^{1/3} (L_0/L_c)^{1/5}$, where $L_0 \simeq 2\varepsilon a_0$ is the length of longitudinal fluctuations, $L_c \simeq \varepsilon \xi (J_0/J_d)^{1/2}$ is the correlation length, $J_0 = 4c\varepsilon_0/3\sqrt{3}\xi\Phi_0$ is the depairing current, ξ is the coherence length, and $\gamma \simeq (J_c\Phi_0/c)^2 L_c$ is the disorder pa-

parameter. Using realistic for the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ superconductor parameters ($\lambda = 500$ nm, $\xi = 4$ nm, and $\varepsilon = 1/7$) and experimental value of the depinning current $J_{c,dyn} < 5$ kA/cm² we obtain the energy $E_p < 2 \cdot 10^{-16}$ erg, which is about 25 times smaller compared to the elastic energy $E_{el} \simeq c_L^2 \varepsilon \varepsilon_0 a_0 \simeq 5 \cdot 10^{-15}$ erg estimated for the $c_L = 0.2$ and $H_{OD} = 1.25$ kOe. The pinning energy induced by vortex interaction with the clusters of oxygen vacancies equals the condensation energy $U_c \approx (H_c^2/8\pi)V_{cl}$, where $H_c = \Phi_0/2\sqrt{2}\pi\lambda\xi$ is the thermodynamic critical field and V_{cl} is the volume of clusters. For spherical clusters with radius $r \simeq \xi$ we obtain the energy $E_p \simeq U_c \approx 10^{-14}$ erg, which is suitable for occurrence of the OD transition in the field of 1.25 kOe.

As it is shown in Fig. 2b, minimum in the $J_{c,dyn}(H)$ curve occurs in a field of 2.5 kOe, which is about two times exceeds the value of H_{OD} . Also, above the minimum position, the current $J_{c,dyn}(H)$ increases with the field more gradually in comparison with increase of the current J_E above the OD transition. This difference can be explained by suppression of the longitudinal and conservation of the transverse pinning barriers, as it was theoretically predicted in [14]. In frames of the "shaking temperature" model [13], this means conservation of the transverse (with respect to vector \mathbf{v}) u_\perp and reduction of the parallel $u_\parallel \propto 1/v$ component of the displacements $u_t = \sqrt{(u_\parallel)^2 + (u_\perp)^2}$ with increased velocity v . In magnetic field $\mathbf{H} \parallel \mathbf{c}$ and in presence of the chaotic pinning potential, spatial distribution of the displacements is isotropic; and in the field $H > H_{OD}$, the displacements $u_{t,L}$, which correspond to the Lindemann criteria, fall in the interval $c_L a_0 (H_{OD}) > u_{t,L} > c_L a_0 (H)$, as it is shown schematically in the inset of Fig. 2b. Density of the displacements (the number of vortex displacements $u_{t,L}$ per unit length of vortex line) $n_{t,L}$ is proportional to the area of ring confined by the upper (solid circle) and lower (dashed circle) boundary of the displacements $u_{t,L}$. Reduction of the component u_\parallel with increased velocity v leads to reduction of the upper boundary (dotted lines for velocities $v_2 > v_1 \neq 0$), and thus to reduction of the density $n_{t,L}$. It is important, that for any finite velocity v the component u_\parallel is finite, and thus the cross-hatched area at the diagram, which corresponds to the displacements $u_{t,L}$, and the density $n_{t,L}$ is also finite. Increase of the field reduces the lower boundary of the displacements $u_{t,L}$, and therefore the density $n_{t,L}$ increases.

Considering that the displacements $u_{t,L}$ produce the dislocations in the VS phase, and increase of the density $n_{t,L}$ results in an increase of the current $J_{c,dyn}$ [19], the field variation of the currents J_E and $J_{c,dyn}$ can be explained in the following way. In low fields, the ordered VS phase, which is characterized by the absence of dislocation and realization of the 1D pinning, is formed, and the currents J_E and $J_{c,dyn}$ decrease with increased field due to enhancement of the vortex-vortex interaction, making difficult to fit the vortices in the pinning landscape. Above the OD transition, the VS phase contains dislocations that results in occurrence of the 3D pinning

[10], and thus the current J_E increases at the transition point H_{OD} due to dimensional crossover in the pinning [20, 21]. Further increase of the current J_E with magnetic field is caused by increase of the density $n_{t,L}$, as it was found in [19]. The density $n_{t,L}$ is smaller in the moving VS phase than in the static VS phase, but it is finite and increases with the field. Therefore, the $J_{c,dyn}(H)$ dependence is determined by competition between decrease of the pinning force caused by enhancement of the vortex-vortex interaction and increase of the pinning force associated with increase of the density $n_{t,L}$. In our measurements, the former mechanism dominates in magnetic fields $H \leq 2$ kOe, while the last one dominates in the fields $H \geq 3$ kOe.

Proposed interpretation agrees with numerical simulations of 2D [22, 23, 24, 25] and 3D [15] VL's in the presence of strong pinning. First, it was shown that in the flux flow mode the disordered state of the VL's is preserved [15, 22, 24, 25], and the transverse barriers remain finite [23, 24]. Second, the $v(J)$ curves cross one another near the OD transition [15]. Third, our interpretation implies that cross-hatched area in the diagram collapses to a segment at $v \rightarrow \infty$, indicating that moving VS can be ordered in agreement with conclusion in [15]. Finally, the onset of ordering of the moving VS phase is manifested as a peak in the $\rho_d(J)$ curves, and the end of ordering corresponds to value of the resistance $\rho_d(J)=1$ [22, 25], and in our measurements peak in the $\rho_d(J)$ curves appears in the fields $H > H_{OD}$. Following computer simulations, we determined the field variation of the velocities v_p and v_{min} , which correspond to the peak and minimum positions in the $\rho_d(J)$ curves respectively. As it is shown in Fig. 3b, the velocity v_p and the difference $\Delta v = v_{min} - v_p$ increase with the field indicating that the critical velocity of the ordering as well as the interval of velocities Δv , in which the ordering realizes, increase with the field. This behavior is plausible considering that the lower boundary of the displacements $u_{t,L}$ decreases with the increased field that requires higher v 's to decrease the amplitude below this boundary. Also, the difference between the upper and lower boundary of the displacements $u_{t,L}$, $\Delta u = c_L[a_0(H_{OD}) - a_0(H)]$, increases with the field that results in increase of the difference Δv .

Our interpretation allows explaining occurrence of the hysteresis effect in the curve $v(J)$ measured with the increased and decreased current in a field of 1.5 kOe, and absence of the hysteresis effect below and quite above the OD transition. Indeed, in close vicinity to the OD transition, $(H/H_{OD} - 1) \ll 1$, the density $n_{t,L}$ in the dynamic VS is much smaller than in static VS, and small increase of the velocity v leads to dynamic transition into the ordered state. In this case the "shaking temperature" model predicts the hysteresis effect, which reflects the "overheated state" of the ordered dynamic VS. The decrease in density $n_{t,L}$ quite above the OD transition is not dramatic, and transition from strongly disordered static VS to less disordered dynamic VS occurs in a wide interval of velocities Δv without hysteresis. It is impor-

tant to notice that the $E(J)$ curves measured after zero field cooling coincide with the $E(J)$ curves measured after non zero field cooling, that indicates the absence of metastable states in the VS. This agrees with experimental studies of the YBaCuO crystals: the metastable states exist in vicinity of the vortex solid - vortex liquid transition, but they disappear below this transition [26].

Recent quantitative theory of the dynamic VS by Rosenstein and Zhuravlev [11] predicts jump-like increase of the pinning force at the OD transition. It is evident that this theory does not describe our results because increase of the currents J_E and $J_{c,dyn}(H)$ occurs in different fields, and field variation of the currents does not show the jump-like increase.

The obtained field variation of the currents J_E and $J_{c,dyn}$, occurrence of the hysteresis effect in close vicinity to the OD transition, and absence of the metastable states in the VS are different from that in superconductors with weak bulk pinning. For example, in crystals NbSe₂ [27] and MgB₂ [5], the current $J_{c,dyn}$ increases in a jump-like manner at the OD transition [27, 28], and the hysteresis effect occurs in rather wide interval of magnetic fields and it is caused by presence of the metastable

states in the VS [5, 27], which are induced the effect of surface barriers [29]. The surface barriers in the NbSe₂ [30] and MgB₂ [4] cause asymmetry of the magnetization loops, and this asymmetry reflects a difference in the barriers for vortex entrance and exit of samples [31]. The magnetization loops of the YBaCuO crystals are symmetric indicating negligible effect of the surface barriers. Therefore obtained field variation of the current J_E corresponds to equilibrium quasistatic VS.

In conclusion, we determined field variation of the critical currents in the quasistatic and dynamic vortex solid. The currents non-monotonously vary with the field, but minimum position in the $J_{c,dyn}(H)$ dependence is shifted to higher fields in comparison with the minimum in the $J_E(H)$ dependence. The difference is interpreted by partial ordering of the vortex solid with increased vortex velocity. The disordered state of the dynamic vortex solid is attributed to preservation of finite transverse pinning barriers that guarantees presence of the transverse vortex displacements suitable for formation of dislocations. This interpretation allows explaining observed increase of the critical current of the dynamic ordering.

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